Transactions of the Korean Nuclear Society Autumn Meeting
ICC Jeju, Korea, May 16-18, 2018

Simulation and Modelling of Cladding Thermo-mechanical Behavior under LOCA

Ashwini Kumar Yadav [a*], Chan Lee [a], Sung-Uk Lee [a], Chang-Hwan Shin [a], Hyo-Chan Kim [a]
[a] *Nuclear Fuel Safety Division, Korea Atomic Energy Research Institute,*
111, Daedeok-Daero 989beon-gil, Yuseong-Gu, Daejeon, 34057, Republic of Korea
[*] *Corresponding author: akyadav@kaeri.re.kr*

1. Introduction

The economic concerns compelling utilities to consider the increase of average burnup for fuel assemblies and to adopt new type of cladding materials to enhance thermal and safety margins. To sustain such aggressive conditions by fuel and reactor core requires new investigations for fuel rod behavior under reference accidental conditions. Keeping in view above facts, a code name 'TRAFR' (**T**ransient **R**esponse **A**nalysis of **F**uel **R**od) is developed to model thermo-mechanical coupled behavior of fuel rod and the simulation results are discussed in this paper.

2. Modelling methodology

The Fig.1 shows details of test section used for simulation of bal1oning phenomenon of cladding at under simulated LOCA scenario (Yadav et al., 2017). The test section was placed inside cylindrical enclosure having water cooled jacket and the cladding was indirectly heated using Tungsten heater with alumina pellets. The configuration factor (F_{ij}) between the fuel rod, heater and enclosure is calculated by Hottel's cross string method. The table 1 shows value of configuration factor calculated by code for various surfaces. Using thermal resistance diagram (shown in Fig.2), by applying kirchorff law to each junction, the equation of radiosity (J_i) can be written as

$$J_i - (1-\varepsilon_i)\sum_{j=0}^{N} J_j F_{ij} = \varepsilon_i \sigma T_i^4$$

These system of linear equations developed for all the surfaces are solved for radiosity by LU factorization method. To calculate surface temperature of fuel rod, an energy balance is performed for each time step using the respective radiosity terms. The energy leaving the surface of fuel rod by radiation can be written as

$$Q_{rad} = A_i\left(\frac{\varepsilon_i}{1-\varepsilon_i}\right)(\sigma T_i^4 - J_i)dt$$

The radiative heat transfer coefficient at the outer surface of clad tube was calculated as:

$$h_{rad} = \frac{Q_{rad}}{T_{clo} - T_{enc}}$$

The convective heat transfer coefficient, h_{conv} is

$$h_{conv} = \frac{k_{gas} Nu}{L}$$

Where the Nusselt number (Nu) and Rayleigh number (Ra) were calculated from the thermo-physical property of argon at bulk temperate.

The radial temperature distribution within fuel rod is calculated by solving the one-dimensional transient heat transfer equation with heat generation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + q''' = \rho C_p \frac{\partial T}{\partial t}$$

subjected to the following boundary conditions,

$$-k\frac{\partial T}{\partial r} = h(T - T_b)$$

at $r = r_c$ and

$$\frac{\partial T}{\partial r} = 0$$

at $r = 0$ using the implicit finite difference method. The gap heat transfer coefficient was calculated by presuming open gap between the pellet and cladding (Lanning and Hann, 1975).

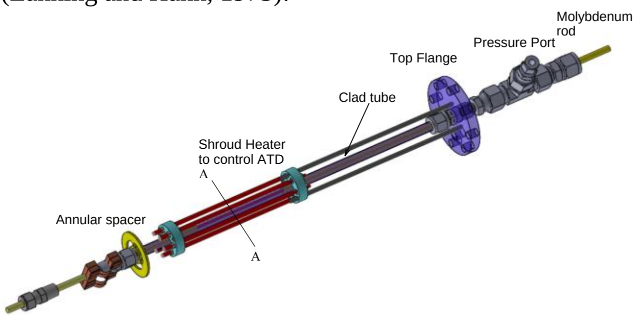

Figure 1: Details of Test section

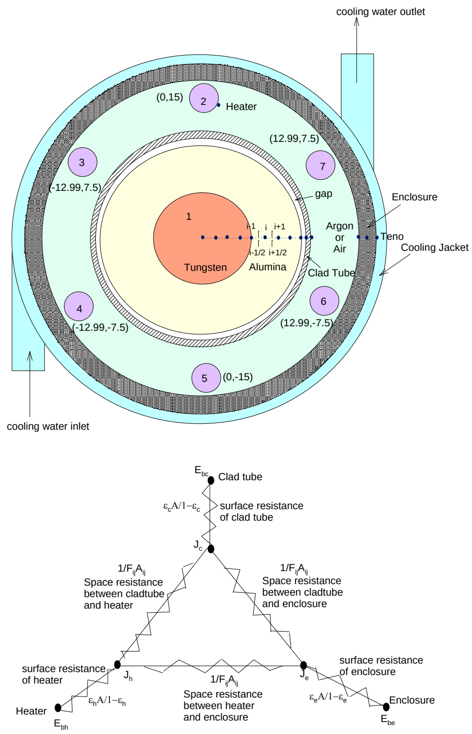

Figure 2: Section A-A, discretization scheme and thermal resistant diagram

By applying energy balance, the surface temperature of shroud heater after each time increment can be calculated as

$$T_{htr}^{n+1} = T_{htr}^{n} + \left(\frac{Q_{heater} - A_{htr}\left(\frac{\varepsilon_{cli}}{1-\varepsilon_{cli}}\right)(\sigma T_{htr}^4 - J_{htr}) - h_{conv}A_{htr}(T_{htr}^n - T_{bulk}^n)}{m\,C_p}\right)dt$$

Similarly, the inside surface temperature of enclosure can be calculated by as

$$T_{enci}^{n+1} = T_{enci}^{n} + \left(\frac{h_{convenc}A_{enc}(T_{bulk}^n - T_{enci}^n) + A_{enc}\left(\frac{\varepsilon_{enci}}{1-\varepsilon_{enci}}\right)(J_{enc} - \sigma T_{enci}^4) - \frac{(T_{enci}^n - T_{enci+1}^n)2\pi K_{enc}}{ln\left(\frac{R_1}{R_0}\right)}}{m\,C_p}\right)dt$$

The total circumferential strain at each time step was calculated as a summation of the thermal, elastic and creep strain.

$$\varepsilon_{total} = \varepsilon_{th} + \varepsilon_{\theta} + \varepsilon_{cr}$$

The thermal strain was calculated as

$$\varepsilon_{th} = \alpha_{th}(T) - \alpha_{th}(T_{ref})$$

The elastic strain at each time step was obtained by a generalized hook law as

$$\text{elastic strain}, \varepsilon_{\theta} = \frac{\sigma_{\theta}}{E}$$

The tangential stress at each time step was compared with the yield stress (Lin, 1977). When the true stress become more than the yield stress, the code calculates creep strain. In the plastic region, the power law-Arrhenius equation for a steady-state creep rate is

$$\dot{\varepsilon} = A_{\theta}\sigma_{\theta}^{n_1}\exp\left(\frac{-C_1}{T}\right)$$

Where A_z , C_1 , n_1 are temperature-dependent creep coefficients (Rosinger, 1984).

The Fig. 3 shows predicted surface temperature of cladding, heater, inside surface of enclosure, radial temperature within alumina, tungsten and gap heat transfer coefficient at center location during ballooning at 8.0 MPa.

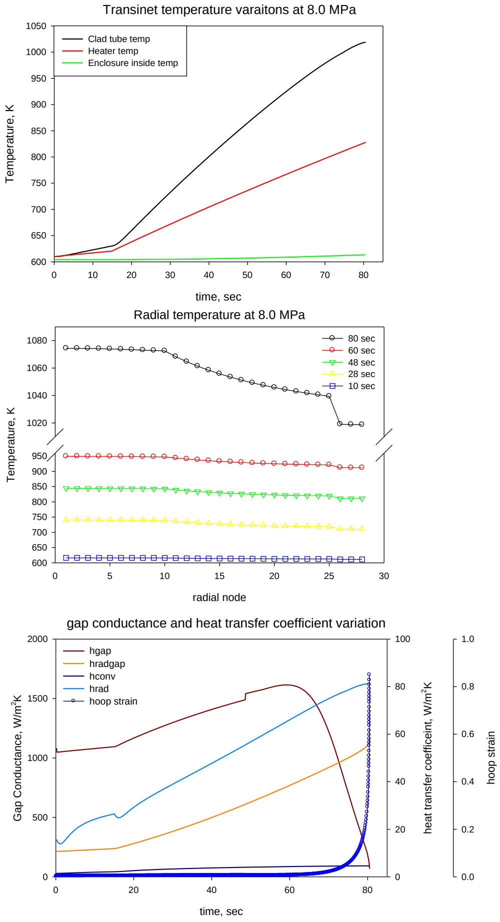

Figure 3: Predicted temperature, gap conductance and hoop strain

3. Conclusions

The code predicted clad tube burst at 1018 K with maximum hoops strain of 0.82. The gap conductance reduced steeply with ballooning and maximum temperature drop of 20 K across the gap was predicted before burst. Maximum value of radiative and convective heat transfer coefficient was 80 W/m^{2}K and 5 W/m^{2}K respectively. Hence, radiation was dominant mode for heat transfer from outer surface of cladding.

4. Acknowledgement

This work has been carried out under the Nuclear R&D Program supported by the Ministry of Science & ICT (NRF-2017M2A8A4015024).

REFERENCES

[1] Yadav, A. K., Shin, C., Lee, S., Kim, H., 2017. Experimental investigations on transient thermo-mechanical behavior of cladding under LOCA using fuel simulator.

[2] Lanning, D. D., Hann, C. R., 1975. Review of Methods Applicable to the Calculation of Gap Conductance in Zircaloy-Clad UO2 fuel rods, BNWL-1894. Battelle, Pacific Northwest Laboratories, Richland, Washington 99352. Report prepared for USNRC.

[3] Rosinger, H. E., 1984. A model to predict the failure of Zircaloy-4 fuel sheathing during postulated LOCA conditions. Journal of Nuclear Materials 120, 41-54.

Table 1: Configuration factor calculated by 'TRAFR'

Surface	Enclosure(0)	Cladtube (1)	Heater(2)	Heater(3)	Heater(4)	Heater(5)	Heater(6)	Heater(7)
0	0.256807	6.78E-02	0.112558	0.112558	0.112558	0.112558	0.112558	0.112558
1	0.37165	0.00	0.104725	0.104725	0.104725	0.104725	0.104725	0.104725
2	0.579719	0.102956	0.00	0.102956	5.57E-02	0.00	5.57E-02	0.102956
3	0.579717	0.102956	0.102957	0.00	0.102956	5.57E-02	0.00E+00	5.57E-02
4	0.579716	0.102957	5.57E-02	0.102956	0.00	0.102956	5.57E-02	0.00E+00
5	0.579717	0.102956	0.00E+00	5.57E-02	0.102956	0.00	0.102957	5.57E-02
6	0.579713	0.102956	5.57E-02	0.00E+00	5.57E-02	0.102956	0.00	0.102956
7	0.579719	0.102956	0.102956	5.57E-02	0.00	5.57E-02	0.102956	0.00